Problems and Prospects for Improving Climate Models: The Story of Clouds

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Abstract

The scientific evidence is now clear that human activities are influencing climate change. These activities include adding carbon dioxide and other gases to the atmosphere that increase the natural greenhouse effect and lead to global warming. They also include adding small particles and other pollutants to the atmosphere. Climate models now tell us with great confidence that, because of these human activities, the 21st century will be much warmer than the 20th century, with significant increases in sea level and changes in weather patterns, among many other serious consequences for people and ecosystems.

Climate models are limited by incomplete understanding of key physical processes, to a far greater extent than by computer limitations or other technical barriers. The improvement of climate models depends on developing new physical understanding and then finding physically realistic algorithms incorporating it. Today, clouds are believed to be the single most uncertain source of uncertainty in climate model forecasts of future climate change, because their interaction with solar and terrestrial radiation is such an important aspect of the climate system. A current dilemma of climate modeling is that model results are strongly sensitive to the treatment of several poorly understood physical processes, especially cloud radiation interactions. Thus, different models with alternative plausible parameterizations often give widely varying results. Yet, we typically have had little basis for estimating which parameterization is more realistic, although most of the global differences in results between leading climate models, as measured by their sensitivity to greenhouse gases, can be traced to different model treatments of cloud radiation interactions.

Cloud radiation interactions are regarded today as one of the most critical areas in global change research. In particular, when climate models are intercompared, cloud radiation parameterizations are responsible for most of the global mean differences in sensitivity to greenhouse gas increases. This fact has become well established through parameterization transplant experiments. In such computational experiments, transplanting the cloud radiation algorithm from one model to another typically causes the recipient model to closely replicate the climate sensitivity of the donor model. The uncertainty in model responses is directly due to a lack of fundamental understanding of the physical processes involved. A major research effort is underway worldwide in response to this challenge. Furthermore, closely related research areas, such as the role of atmospheric aerosols in climate, are also beginning to receive the attention they deserve.

On even the simplest theoretical grounds, it is not surprising that climate is extremely sensitive to cloud amount. Similar arguments can be made to show that climate also ought to depend strongly on other cloud properties, such as cloud height and cloud liquid water or ice content. In fact, an easily stated but still unsolved major problem is to understand why the global cloud cover is now about 60% and why the planetary albedo is now about 30%. Were these quantities the same during the ice ages? What mechanisms maintain the system at the present values of these key parameters, and how stable are these mechanisms to perturbations, such as those due to changing greenhouse gas concentrations? We simply do not know. Until we find out, the "confidence limits" or "error bars" on the results of climate model greenhouse simulations will be much too large.

For many years, virtually all global climate model or general circulation model (GCM) treatments of clouds were based on simple algorithms relating cloud amount to relative humidity. Such parameterizations usually produced positive global average cloud radiation feedbacks in numerical experiments simulating greenhouse-induced climate change. For example, in a typical integration performed with a GCM developed in the 1970s, a climate warming due to increased atmospheric carbon dioxide concentrations would lead to increased average cloud heights and/or decreased average cloud amounts. It is easy to understand qualitatively why such feedbacks were positive. First, higher clouds are colder and so less effective infrared emitters, and they generally have lower albedos than lower clouds, so the cloud height feedback was positive (i.e., the change in clouds produced by the warming tended to amplify the warming). Second, average model clouds, like average real clouds, contribute more strongly to the planetary albedo than to the planetary greenhouse effect (in technical terms, the short-wave cloud forcing is larger than the long wave cloud forcing by about 20 W m-2). Hence, a reduction in cloud amount reduces the short wave effect more than the long wave effect of clouds. Thus, the cloud amount feedback is also positive.

Climate models are now more numerous and more complicated, however, and model responses to increased greenhouse gas concentrations are more varied. GCMs today attempt to take into account a broader range of physical processes involved in cloud radiation feedbacks. The climate modeling community now realizes clearly that cloud feedback processes are not limited to macrophysical cloud properties, such as cloud amount and cloud altitude. In recent years, many GCMs have begun to include cloud parameterizations which include explicit treatments of cloud physics.

Clouds have a powerful effect on the radiation budget of the earth. The reasons are obvious: clouds contribute to both the greenhouse effect, which warms the planet, and to the earth's reflectivity, or albedo, a competing cooling effect. Studies in which alternative cloud parameterizations can be tested against observations show great promise for improving our understanding of clouds and their influence on climate. Ultimately, this improved understanding will find its way into the representations of cloud used in general circulation models.

Improving the realism of this aspect of models is a key to improving the model simulations of climate change. We know that the leading models of today differ by a factor of three among themselves when they are compared in terms of their simulation of the global average surface temperature increase due to a prescribed climate forcing, such as doubling the atmospheric concentration of carbon dioxide. Most of this factor of three is due to the different ways in which the models represent clouds and cloud radiation interactions. We know, for example, that in many climate models, cloud amounts in a warmer climate tend to be somewhat less than in the present-day climate, and cloud altitudes tend to be somewhat greater. These changes lead to positive feedbacks, increasing the apparent sensitivity of the model climate to the imposed forcing which led to the original warming, such as an increase in carbon dioxide. However, the nature and strength and especially the regional aspects of these feedbacks differ greatly from model to model. For this reason, many scientists regard cloud radiation processes as the most critical area of climate modeling research, deserving highest priority for climate research resources.

Simple black-body radiative equilibrium calculations suggest that changes in cloud amount by only one or two percent might double or halve the model sensitivity to carbon dioxide. This feedback occurs because clouds, which cover about half the earth's surface, are responsible for about two-thirds of the planetary albedo. At present, the albedo is about 30%. An albedo change of only 1% would cause a change in the blackbody radiative equilibrium temperature of about 1°C. This is about the same black-body temperature response as would occur in response to adding 4 W m-2 to the earth's surface radiation budget, which is approximately the direct radiative forcing equivalent to doubling the atmospheric carbon dioxide concentration.

Much research is now underway exploring the role that microphysical properties of clouds might play in affecting climate change. These processes might well lead to strong feedbacks. For example, as the climate warms because of an increase in the greenhouse effect, the entire hydrological cycle may accelerate. More water may evaporate from the oceans, and the atmospheric concentration of water vapor may increase. Because of the greater availability of water vapor, some clouds in the warmer climate may have more liquid water or ice than their counterparts in today's climate. In general, a higher liquid water or ice content is thought to lead to a higher albedo, hence a negative feedback. However, for thin clouds, particularly cirrus, the cloud greenhouse effect may also increase. In addition, it is not at all clear that cloud water content will change in any systematic way as climate alters. It may also be too simplistic to look on temperature as a dominant controlling factor for cloud microphysics.

Furthermore, the way in which cloud water or ice content depends on temperature, even in the present climate, is not well understood. Simple theory and aircraft data and some modeling studies support the idea of higher cloud water contents in warmer clouds. Some recent interpretations of satellite data, however, suggest that even the sign of the temperature dependence may be in doubt. It seems unlikely that any simple universal relationship is valid.

Additionally, the radiative properties of clouds also depend on factors such as the size distribution of cloud droplets, the shape of ice particles, and other factors. Despite much observational and theoretical work in recent years to explore these issues, we are still far from a comprehensive physical understanding of them.

Nevertheless, several leading atmospheric general circulation modeling groups in different countries have now incorporated this class of cloud feedback mechanisms in one way or another. In a typical approach, cloud liquid water or ice content is included in the model as an additional prognostic variable, just like temperature, wind velocity and water vapor. The physical processes which act as sources and sinks for cloud water or ice, such as evaporation, condensation and precipitation, are simulated parametrically. In other words, the effects of these processes on the cloud water and ice budget are represented by simple formulas relating these processes to the large-scale variables which the model predicts explicitly.

The results of climate change simulations with these models confirm the strong sensitivity of climate to cloud microphysics. In one striking set of numerical experiments, a British general circulation modeling group (Senior and Mitchell, 1993) produced global average surface temperature changes (due to doubled carbon dioxide) ranging from 1.9 to 5.4°C, simply by altering the way in which these cloud-climate feedback mechanisms were treated in the model. They tested four different parameterizations, successively incorporating relative humidity cloud, prognostic cloud water, phase changes from water to ice, and interactive radiation dependent on cloud microphysics. Their cloud water algorithm was that of Smith (1990). It is somewhat unsettling that the results of a complex model can be so drastically altered by what amounts to changing a few lines of code, essentially replicating the factor-of-three difference in global sensitivity between GCMs that has been revealed by extensive model intercomparisons (Cess et al., 1989). Clearly, further research is urgently required to understand this class of physical processes better and to incorporate this understanding in models.

One particularly promising avenue of research is to combine process modeling with intensive field observations and with research using general circulation models. For too long, research in this field has been characterized by too many plausible cloud radiation parameterizations and too little effort to test them empirically. Now that appropriate observations and novel modeling tools are at last becoming available, we may anticipate rapid progress in this critical area of climate research.

Recent research has led to a greatly increased understanding of the uncertainties in today's climate models. In attempting to predict the climate of the 21st century, we must confront not only computer limitations on the affordable resolution of global models, but also a lack of physical realism in attempting to model key processes. Until we are able to incorporate adequate treatments of critical elements of the entire biogeophysical climate system, our models will remain subject to these uncertainties, and our scenarios of future climate change, both anthropogenic and natural, will not fully meet the requirements of either policymakers or the public. The areas of most-needed model improvements are thought to include air-sea exchanges, land surface processes, ice and snow physics, hydrologic cycle elements, and especially the role of aerosols and cloud radiation interactions.

Only about 70% of the sunlight intercepted by the Earth is available to drive the climate system. The other 30% (the planetary albedo) is simply reflected to space, mainly by clouds, which cover some 60% of the surface of the planet. On average, clouds reduce the global average absorbed solar radiation by about 50 Wm-2. Clouds also help to trap terrestrial radiation, contributing about 30 Wm-2 to the greenhouse effect. The net cloud radiative forcing is the difference, approximately 20 Wm-2. Thus, the albedo effect dominates, and the net effect of clouds at present is to cool the Earth. However, the plain fact is that we lack a basic understanding as to why the global cloud amount is about 60%, why the planetary albedo is about 30%, how these and other fundamental quantities may have changed as climate changed over geological time, and how they may change in the future.

One simple way to appreciate the climatic significance of clouds is to compare the cloud radiative forcing magnitudes given above with the direct radiative effect of doubling the concentration of atmospheric carbon dioxide, which is only about 4 Wm-2. Thus, if a climate change caused by increased CO2 were to result in even a small change in the cloud amount, the cloud feedback effect might well be important. Furthermore, even if global average cloud amount did not change appreciably in response to a changed climate, the spatial and temporal distribution of clouds might well be altered, as might other critical quantities, such as cloud altitude and cloud radiative properties. All of these changes in clouds could lead to significant feedback effects. Until cloud processes are much better understood, and until this understanding is incorporated in our models, the model results will always be subject to major uncertainties.

A serious dilemma of climate modeling today is that model results are extremely sensitive to parameterizations of several poorly understood physical processes. As a result, models with different plausible parameterizations give very different results. Unfortunately, we have no firm basis for knowing which parameterization is more nearly "correct." Perhaps the most dramatic example of this dilemma is the mystery of cloud radiation interactions.

Unfortunately, it is not known which of these parameterizations is the most realistic, or even if any of them captures the essential feedback processes of actual clouds. Furthermore, other GCM groups have obtained different results by trying other ways of incorporating cloud microphysical processes and their radiative interactions (e.g., Le Treut and Li, 1988, 1991; Roeckner et al., 1987), in contrast to the approach which Senior and Mitchell (1993) followed. There is thus a clear need to intercompare these approaches with one another, and, even more importantly, to validate them against observations, so as to evaluate the strengths and weaknesses of each.

It is noteworthy that the sensitivity of model-simulated climates to changes in atmospheric carbon dioxide concentration has undergone major fluctuations in recent years. The equilibrium global average surface temperature change in response to a carbon dioxide doubling, based on GCM results from models developed in the mid-1970s, was typically between 2 and 3 deg C. By the middle to late 1980s, the range of typical GCM sensitivities was between 4 and 5 deg C. Nearly all of the increase in sensitivity could be traced to cloud radiation interactions. More recently, several GCMs incorporating more complex cloud algorithms, including some feedbacks arising from cloud microphysical processes, have shown reduced sensitivity to changing greenhouse gas concentrations (Senior and Mitchell, 1993).

In the earlier models, clouds were treated in a very simplistic way, and their ability to undergo changes, and thus to influence climate variability, was limited. In some GCMs, in fact, clouds and their radiative properties were prescribed once and for all and then held constant, so that no feedbacks were possible. Later models, by contrast, featured clouds which could and did change their absolute amount and their height distribution in response to changes in atmospheric water vapor content (e.g., Slingo, 1987). As the simulated clouds changed, so did their ability to contribute to both planetary reflectivity, or albedo, and to the greenhouse effect.

One type of problem is to characterize clouds, once they are formed in GCMs, i.e., to determine their radiative properties. Many unanswered questions are tied to this type of problem. For example, does carrying cloud liquid water as a prognostic variable offer real advantages in terms of being able to specify cloud radiative properties realistically? Or is it feasible to specify these properties directly from the other large-scale GCM fields? Some recent work (e.g., Tselioudis et al., 1993) suggests that it may be difficult or impossible to infer cloud radiative properties as simple functions of temperature and other variables carried explicitly by GCMs, but much research remains to be done on cloud characterization.

Another class of problems involves cloud formation. Here the goal is to develop parametric treatments which enable GCMs to simulate when and where clouds occur. In current GCMs, typical algorithms relate cloud amount to GCM variables such as relative humidity. Then partial cloud cover is handled by weighting clear sky and overcast radiative calculations by the predicted cloud fraction. One promising alternative approach is to specify clouds stochastically, i. e., to develop parameterizations which yield probability distributions for variables such as the size and spacing of clouds (e. g., Malvagi et al., 1993).

New theoretical tools have been developed to aid in validating parameterizations against observational data. One such tool is the single-column model or SCM (Somerville, 2000). An SCM is a computationally efficient and economical one-dimensional (vertical) model, resembling a single column from a GCM grid (e. g., Iacobellis and Somerville, 1991a, b). The model contains a full set of modern GCM parameterizations of subgrid physical processes. To force and constrain the model, the advective terms in the budget equations are specified observationally (Randall et al., 1996).

The trend of increased reliance on observational field programs which can provide both satellite and in-situ data, together with the development of SCMs and other means of using these data, is a powerful combination (e. g., Iacobellis and Somerville, 2000). This trend holds great promise for improving our understanding of cloud radiation processes and for the future improvement of the treatment of these processes in climate models (e.g., Lee et al., 1997).

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